

Polarimetric studies of comet Halley

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Abstract

In the present work, the non-spherical grain characteristics of comet Halley are analysed using the T-matrix method at $\lambda = 0.365, 0.485$ and $0.684\mu m$ respectively. In order to analyse the polarisation data of comet Halley, the dust size distribution function derived by Das et al. (2004) for comet Halley is used in the present work. The size range of the grains is taken to be $0.01\mu m \leq s \leq 3\mu m$. Using the T-matrix method, the best fit values of complex refractive indices (n, k) and aspect ratio (E) are determined at three different wavelengths $0.365, 0.485$ and $0.684\mu m$ and the corresponding values are given by $(1.380, 0.043, 0.962)$, $(1.378, 0.049, 0.962)$ and $(1.377, 0.058, 0.962)$ respectively. After comparing the above result with Mie theory result, it is found that prolate grains give the best fit to the observed polarisation data of comet Halley. Also the negative polarisation behaviour of comet Halley is discussed thereafter.

Key words: comets: general — dust, extinction — scattering — polarisation

1. Introduction

The study of polarisation of the scattered radiation from comets, over various scattering angles and wavelengths, gives important information about the nature of cometary dust grains. However at certain wavelengths, the polarisation features are contaminated due to the polarisation present in the cometary molecular line emission. Since the last apparition of comet Halley, observers have been using a set of filters (centered at $\lambda = 0.365\mu m, 0.485\mu m$ and $0.684\mu m$) known as IHW (International Halley Watch) filters to avoid contamination by line emission.

The analysis of polarisation data gives information about the physical properties of the cometary grains, which include size distribution, shape and complex refractive index. The *in situ* dust measurement of comet Halley gave the first direct evidence of grain mass distribution (Mazets et al. 1986). Mukai et al. (1987) and Sen et al. (1991a) analysed the polarisation data of comet Halley using the power law dust distribution (Mazets et al. 1986) and Mie theory, and derived a set of refractive indices of cometary grains. The dust distribution function derived by Mazets et al. (1986) is actually based on only Vega 2 results while Lamy et al. (1987) derived the grain size distribution for Halley by comparing the data from spacecrafts Vega 1, Vega 2 and Giotto. However, Das et al. (2004) also analysed the polarisation data of comet Halley using dust distribution function suggested by Lamy et al. (1987).

The polarisation data of several other comets were analysed by Das et al. (2004) using Mie theory. They discussed

the grain aging of comets by solar radiation for four non-periodic comets (Hyakutake, Austin, Bradfield, Levy 1990XX) and found out an empirical relation between relative abundance of coarser grains index (g) and perihelion distance (q) of the form $g = -2.5q^{2/3}$. Das et al. (2004) further commented that comets whose grains are processed more by the solar radiation do contain relatively smaller number of finer grains. From their work, it has been found that the grains of comet Levy 1990 XX are much smaller, as compared to the grains of Hyakutake, Austin, Bradfield, Hale-Bopp and Halley.

Several investigators made useful polarimetric measurements of comet Halley through IHW filters (Bastien et al. 1986, Kikuchi et al. 1987, Le Borgne et al. 1987, Sen et al. 1991a, Chernova et al. 1993). The polarisation data of comet Halley were analysed using Mie theory which assumes the dust particles to be spherical (Mukai et al. 1987, Sen et al. 1991a, Das et al. 2004). But it is now accepted that cometary grains are not spherical and may be *fluffy aggregates* or *porous*, with irregular or spheroidal shapes (Greenberg & Hage 1990). The measurement of circular polarisation of comet Hale-Bopp (Rosenbush et al. 1997) also reveals that cometary grains must be composed of non-spherical particles. Thus the polarimetric data analysis using Mie theory will give less exact results. In order to study the irregular grain characteristics of comets, Discrete Dipole Approximation (DDA see viz. Draine 1988), T-matrix theory (Waterman 1965) etc. are used. Xing & Hanner (1997) have done elaborate calculations with porous grains of different shapes and sizes using DDA method. Petrova et al. (2000) have shown that aggregates composed of touching spheres with size parameters 1.3 - 1.65 display properties typical of cometary particles. Their results on the aggregates indicate that more

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compact particles have a more pronounced negative branch of polarisation. However, the DDA method requires considerable computer time and memory. The T-matrix code on the other hand (Mishchenko et. al., 2002) runs much faster and the results obtained can be tuned easily since the input parameters to the code can be adjusted and rerun in a short time. Using the T-matrix code, Kerola & Larson (2001) analysed the polarization data of comet Hale-Bopp and found the grains to be mostly prolate in shape in that comet. Recently Das & Sen (2006) (our earlier work) using the T-matrix code found that, the prolate grains can explain the observed polarization in a better way as compared to the other shapes in comet Levy 1990XX.

In the present study, the non-spherical grain characteristics of comet Halley are analysed using Mishchenko's (1991, 1998) T-matrix code. The results obtained from the T-matrix code are compared with the Mie theory results. Also the negative polarisation behaviour of comet Halley is discussed thereafter.

2. Grain characteristics of comet Halley

Polarimetry in the continuum has always been considered as an important technique in the study of cometary dust properties. The observed linear polarisation of comets is generally a function of (i) wavelength of incident light (λ), (ii) Scattering angle, θ ($= 180^\circ - \text{Phase angle}$), (iii) the geometrical shape (E) and size (s) of the particle and (iv) the composition of dust particles in terms of complex values of refractive index, m ($= n - ik$). The shape of a spheroid can be specified by the axial ratio, E ($= a/b$). It is to be noted that $E > 1$ for oblate spheroids, $E < 1$ for prolate spheroids and $E = 1$ for spheres.

2.1. In situ measurements of comet Halley

During the last apparition of comet Halley, *in situ* analysis of comet Halley has been made possible. Several spacecrafts on board Vega 1, Vega 2 and Giotto carried out important measurements to determine the number density of particles of given masses. Based on SP-2 experiment on-board Vega space-craft, Mazets et al. (1986) had determined a set of power laws (with separate indices for different mass ranges) for the particle mass distribution over the range 10^{-16} g to 10^{-7} g. Assuming the grain bulk density to be 1 g cm^{-3} , Mukai et al. (1987) derived the dust size distribution function for comet Halley using the particle mass distribution suggested by Mazets et al. (1986). Based on this size distribution and Mie scattering formulation, Mukai et al. (1987) and Sen et al. (1991a) analysed the polarisation data of comet Halley. However, Lamy et al. (1987) combined the *in situ* dust measurements from the Vega 1, Vega 2 and Giotto and modelled the dust mass distribution function.

Actually, the dust mass distribution function suggested by Mazets et al. (1986) is based on only Vega 2 results, while the work of Lamy et al. (1987) is based on the results of three space-crafts. Further, the size distribution function derived by Mukai et al. (1987) on the basis of the work reported by Mazets et al. (1986) has three discrete size ranges and the size distribution function changes its value abruptly over the three ranges due to the presence of three distinct values of power law index (Das et al. 2004). But the size distribution function obtained by Lamy et al. (1987) has a smooth behaviour. So, Das et al. (2004) followed the work of Lamy et al. (1987) and derived

the dust size distribution function for comet Halley. Using that size distribution function, they analysed the polarisation data of comet Halley and found out a set of complex refractive indices (n, k) which best match the observed polarisation data.

The dust size distribution function $N(s)$ (with a bulk density of dust grain, $\delta = 2.2 \text{ g cm}^{-3}$) for Halley derived by Das et al. (2004), on the basis of work reported by Lamy et al. (1987) is given by

$$\log N(s) = a(\log s)^2 + b(\log s) + c \quad (1)$$

where $a = -0.2593$, $b = -4.422$ and $c = -15.06$.

It may be noted that the grain size distributions used by Mukai et al. (1987), or the one derived from Lamy et. al. (1987)(Ref. Eqn 1) are basically the ones obtained from the last apparition of comet Halley in 1985-86 and were used in explaining mostly the polarisation properties of comets (Das et al. 2004).

Using Mie scattering theory and size distribution function (Eqn 1), Das et al. (2004) analysed the polarisation data of comet Halley and determined the best fit values of (n, k) at which the sum of squares of difference between expected and observed values of polarisation (χ^2 -value) becomes minimum at $\lambda = 0.365, 0.485$ and $0.684 \mu\text{m}$ respectively.

In the present work, 'spheroidal dust grain model' is proposed for Halley to study the linear polarisation data of that comet using the dust size distribution function (Eqn (1)) and the T-matrix method.

2.2. Spheroidal grain model

It is now accepted that cometary grains are not spherical and may be irregular or spheroidal in shapes (Greenberg & Hage 1990). As already discussed the T-matrix method provides a powerful tool to study the spheroidal grains in comets. This method was first introduced by Waterman (1965) for studying electromagnetic scattering by single, homogeneous non-spherical particles. In this paper, calculation has been carried out for randomly oriented spheroids using Mishchenko's (1998) single scattering T-matrix code, which is available in <http://www.giss.nasa.gov/~crim>. The important feature of T-matrix approach is that it reduces exactly to the Mie theory when the particle is a homogeneous or layered sphere composed of isotropic materials.

Several investigators studied irregular grain properties of comets using T-matrix theory (Kolokolova et al. 1997, Kerola & Larson 2001, Das & Sen 2006). Kerola & Larson (2001) analysed the polarisation data of comet Hale-Bopp and found prolate grains to be more satisfactory than other shapes in comet Hale-Bopp. Recently, Das & Sen (2006) studied the polarisation data of comet Levy 1990XX using the T-matrix method and discovered that the prolate shape of cometary grains can well fit the observed data. Since no *in situ* dust measurements were made on comet Hale-Bopp and comet Levy 1990XX, power law distribution (Hansen & Travis, 1974) were used in both the cases. Further, the index of refraction for olivine (1.63, 0.00003) was taken in those two comets for the analysis of polarisation data.

Using Mie scattering theory and grain model of Mazets et al. (1986), Mukai et al. (1987) analysed comet Halley and found a set of three complex refractive indices (n, k) at three IHW

filters which best match their observation. Sen et al. (1991a) combined their polarimetric observations with those of other investigators and estimated (n, k) values which are slightly different from those of Mukai et al. (1987). Based on the dust size distribution function (eqn (1)) and Mie theory, Das et al. (2004) also analysed the data and found a set of refractive indices (n, k) for comet Halley. Lamy et al. (1987) denoted the hypothetical refractive indices (n, k) emerging out from these Mie calculations as ‘Silicate B’.

In the present work, the data is compiled on the polarisation measurements of comet Halley that were made through IHW filters and published in various journals (Bastien et al. 1986, Kikuchi et al. 1987, Le Borgne et al. 1987, Sen et al. 1991a, Chernova et al. 1993). Here, equation (1) is considered for the grain size distribution.

The detectors on-board the Vega and Giotto spacecrafts had sensitivities as low as 10^{-16} g, and it was observed that the particle number density continued to increase till the detection limit was reached (Mazets et al. 1986). Assuming particles of density 1 or 2.2 g cm^{-3} , one can find a lower limit for the particle radius of $0.01 \mu\text{m}$ (Das et al. 2004). Thus the minimum radius of the grains can be fixed at $0.01 \mu\text{m}$. It is to be noted that in the present case, the T-matrix code can safely run on a computer when the *size parameter*, $X (= 2\pi s/\lambda)$ is less than 52. The choice of $\lambda = 0.365, 0.485$ and $0.684 \mu\text{m}$ gives the maximum allowable radii of the dust grain to be roughly $3 \mu\text{m}$, $4 \mu\text{m}$ and $5.5 \mu\text{m}$ respectively. In the present work, the maximum radius of the dust grains is thus fixed at $3 \mu\text{m}$. Hence in order to analyse the polarimetric data of comet Halley at $\lambda = 0.365, 0.485$ and $0.684 \mu\text{m}$ respectively, the size range of the grains is taken as $0.01 \mu\text{m} \leq s \leq 3 \mu\text{m}$.

Using the T-matrix method, the best fit values of (n, k) and E are determined at which the sum of squares of differences between calculated and observed values of polarisation (χ^2 -value) becomes minimum. These values are listed in **Table-1**. No such good fit has been observed for oblate shapes. The calculations are repeated for spherical grains ($E=1$), keeping (n, k) fixed, using Mie theory at $\lambda = 0.365, 0.485$ and $0.684 \mu\text{m}$ respectively. It is clear from **Table-1** that data fits well for prolate grains with $E=0.962$ at $\lambda = 0.365, 0.485$ and $0.684 \mu\text{m}$ respectively.

Greenberg & Li (1996) studied interstellar dust polarisation and found that prolate grains can give more satisfactory results as compared to other shapes. Prolate spheroids are a natural result of the process of *clumping* in the proto-solar nebulae (Kerola & Larson 2001). Thus the findings of prolate grains in comet Halley strengthen the concept that cometary grains are not of spherical shape.

In **Fig 1**, **Fig 2** and **Fig 3**, the expected polarisation curves have been generated using the T-matrix code on the observed polarisation values reported by various authors at wavelengths $0.365, 0.485$ and $0.684 \mu\text{m}$ respectively.

3. Discussions

In the present paper, a simple spheroidal model has been proposed to study the non-spherical grain characteristics of comet Halley. It can be seen from the present analysis that the prolate shape of cometary grains are more satisfactory in comet Halley.

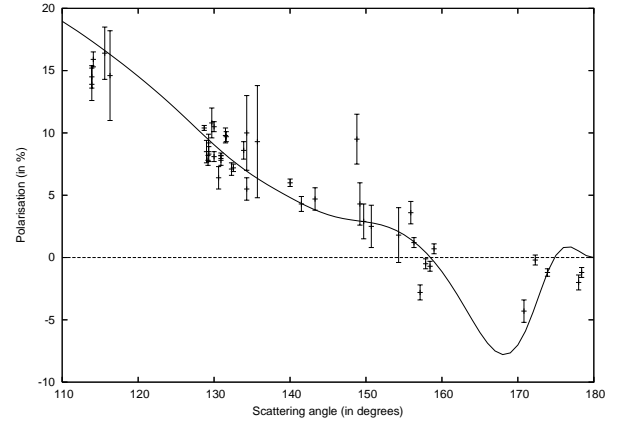


Fig. 1. The observed polarisation values of comet Halley at $\lambda = 0.365 \mu\text{m}$. The solid line represent the best fit polarisation curve obtained from the T-matrix code with $n = 1.380$, $k = 0.043$ and $E = 0.962$.

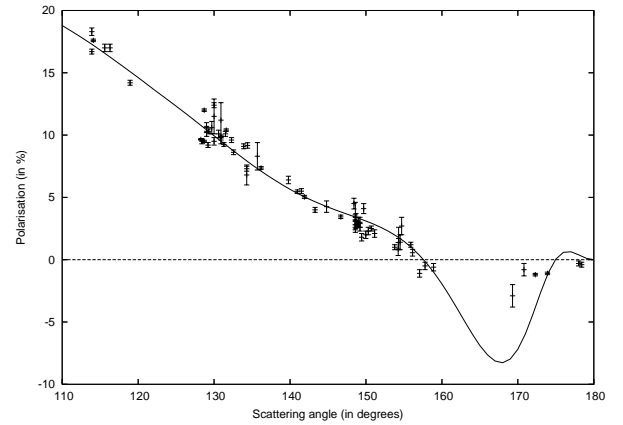


Fig. 2. The observed polarisation values of comet Halley at $\lambda = 0.485 \mu\text{m}$. The solid line represent the best fit polarisation curve obtained from the T-matrix code with $n = 1.378$, $k = 0.049$ and $E = 0.962$.

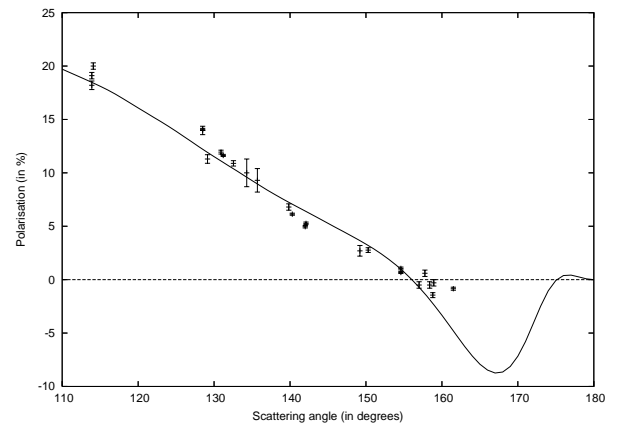


Fig. 3. The observed polarisation values of comet Halley at $\lambda = 0.684 \mu\text{m}$. The solid line represent the best fit polarisation curve obtained from the T-matrix code with $n = 1.377$, $k = 0.058$ and $E = 0.962$.

Table 1. The (n, k) values and E obtained in the present work for comet Halley at different wavelengths.

λ (in μm)	Scattering angle range (in degree)	No. of data points	n	k	E	χ^2_{min}	Source of polarisation data
0.365	114 - 178	43	1.380	0.043	0.962	7.73	Bastien et al. (1986)
					1.000	7.91	Kikuchi et al. (1987)
0.485	114 - 178	72	1.378	0.049	0.962	31.85	Le Borgne et al. (1987)
					1.000	32.25	Sen et al. (1991a)
0.684	114 - 162	25	1.377	0.058	0.962	68.99	Chernova et al. (1993)
					1.000	71.10	

This nature of cometary grain is also observed in comet Hale-Bopp (Kerola & Larson 2001) and comet Levy 1990XX (Das & Sen 2006). Since a good number of polarisation data is available for comet Halley over a wide scattering angle range, it is needless to say that the data analysis will give more accurate results as compared to other comets. To study other comets, Halley is always taken as the reference comet for all types of discussion. Thus, it can be inferred from the above analysis that the dust grains in comets are *not perfectly spherical*.

The negative polarisation behaviour is one of the important phenomena observed in comets. Several comets show negative polarisation beyond the 157° scattering angle (Kikuchi et al., 1987; Chernova et al., 1993; Ganesh et al., 1998 etc.). Many investigators (Greenberg & Hage 1990; Muinonen 1993, Tanga et al. 1997, Levasseur-Regourd et al. 1998 etc.) have discussed the cause of negative polarisation in comets. The *coherent back scattering* mechanism suggested by Muinonen(1993) has been used to explain the negative polarisation. The *fluffy aggregate model* originally proposed by Greenberg and Hage (1990) and later adopted by Xing and Hanner (1997) are also used for the study of negative polarisation in comets. Tanga et al. (1997) and Levasseur-Regourd et al. (1998) suggested that *multiple scattering* may well explain the negative polarisation because lower polarisation is found in the near-nucleus region of comets where dusty jets are most pronounced. Kerola & Larson (2001) also suggested that combination of viewing geometry effects and enhanced multiple scattering might provide a quantitative explanation of the negative polarisation beyond 160° . Many investigators (Mukai et al. 1987; Sen et al. 1991a, 1991b; Joshi et al. 1997; Das et al. 2004 etc.) have generated expected polarisation curve using Mie theory that shows negative polarisation beyond 157° . In the present work, the negative polarisation values have been successfully generated in comet Halley using the T-matrix code for $\theta > 157^\circ$. Das & Sen (2006) analysed the comet Levy 1990XX using the T-matrix theory which reproduced the negative branch of observed polarisation, but their analysis using Mie theory did not show any negative polarisation curve.

Greenberg & Hage (1990) originally proposed the presence of large numbers of *porous* grains in the coma of comets to explain the spectral emission at $3.4 \mu m$ and $9.7 \mu m$. Dollfus (1989) discussed the results of laboratory experiments by microwave simulation and laser scattering on various complex shapes with different porosities. The results of *in situ* measurements carried out on the Giotto spacecraft at comet Halley (Fulle et al. 2000) and the analysis of the infrared spectra of comet Hale-Bopp (Moreno et al. 2003) also agrees with the

model of aggregates. It is clear from recent modeling of optical (Kimura 2001, Petrova et al. 2000 etc.) and thermal-infrared observations (Lisse et al. 1998, Harker et al. 2002), and especially from the Stardust returned samples, that comet dust consists of irregular, mostly aggregated particles.

Xing & Hanner (1997) have done calculation with porous grains of various shapes and sizes using DDA method. Moreno et al. (2003) studied the composite grains using the DDA method for modelling comet Hale-Bopp's dust grains in the mid infrared spectrum. Gupta et al.(2006) also studied the angular distribution of the scattered intensity and linear polarization of composite cometary grains using the DDA method. They used the size range ' s ' from 0.05 to $1.0 \mu m$, which corresponds to equivalent volume size parameter $X = 2\pi s/\lambda$ from 0.14 to 3.0 at the wavelength of $2.2 \mu m$, where ' s ' is the radius of the sphere of equivalent volume of the host grain. However, the DDA method requires considerable computer time and memory. The DDA code allows accurate calculations of electromagnetic scattering from targets with size parameter $X < 15$ provided the refractive index m is not large compared to unity ($|m - 1| < 2$) (Draine & Flatau, 2004). It is to be noted that the choice of $\lambda = 0.365 \mu m$ gives the value of ' s ' to be less than $0.9 \mu m$. Thus using the DDA code, it is not possible to study the scattering properties of composite grains if we consider $s > 0.9 \mu m$. Using the N-sphere method, Petrova et al. (2000) have shown that irregularly structured aggregates composed of a moderate number of touching spheres (< 50) with size parameters $1.3 - 1.65$ display properties typical of cometary particles. Their results on the aggregates indicate that more compact particles have a more pronounced negative branch of polarisation. The N-sphere approach is based on the calculation of clusters of T-matrices and provides an accurate solution for randomly oriented arbitrarily shaped aggregates of spherical monomers (Mackowski and Mishchenko 1996). The available computer restricted the size of the monomers to a size parameter $X = 2.5$ only and the number of monomers within the aggregate to 43. Thus, because of the need for a very large amount of CPU time and memory storage, we could not extend our analysis to published polarisation data of comet Halley at $\lambda = 0.365, 0.485$ and $0.684 \mu m$ respectively using the DDA code and the N-sphere approach, as the size parameter become too large to prevent polarisation calculations with the available numerical codes and computer facilities. The problems can be overcome only if a significant improvement in the particle scattering codes and/or computer speed takes place.

4. Conclusions

Based on the *in situ* dust measurements and ground-based polarimetric observations of comet Halley and also on the T-matrix theory, the following conclusions can be drawn from the present work:

1. The complex refractive indices and shape parameter of Halley's grains as derived from present work are: (1.380, 0.043, 0.962), (1.378, 0.049, 0.962) and (1.377, 0.058, 0.962) at $\lambda = 0.365, 0.485$ and $0.684\mu\text{m}$ respectively.
2. By observing χ^2 -values in **Table-1**, one can say that prolate grains can give better fit to the observed polarisation data.
3. The expected negative polarisation values have been successfully generated for comet Halley using the T-matrix method.
4. The above model is suggested based on calculations which use T-matrix theory, meaningful only for homogeneous spheroidal particles. However, as cometary grains are *porous*, a follow-up paper is planned where calculations will be done with more realistic *porous* grains.

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Table 1. The (n, k) values and E obtained in the present work for comet Halley at different wavelengths.

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					1.000	32.25	Sen et al. (1991a)
0.684	114 - 162	25	1.377	0.058	0.962	68.99	Chernova et al. (1993)
					1.000	71.10	